ORIGIN OF PULSED EMISSION FROM THE YOUNG SUPERNOVA REMNANT SN 1987A

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ABSTRACT

To overcome difficulties in understanding the origin of the submillisecond optical pulses from SN 1987A we apply a model similar to that of Kundt and Krotscheck for pulsed synchrotron emission from the Crab. The interaction of the expected ultrarelativistic $e^{\pm}$ pulsar wind with the pulsar dipole electromagnetic wave reflected from the walls of a "pulsar cavity" within the SN 1987A nebula can generate pulsed optical emission with efficiency at most $\eta_{max} \approx 10^{-3}$. The maximum luminosity of the source is reproduced and other observational constraints can be satisfied for an average wind energy flow $\approx 10^{38}$ erg/(s·steradian) and for electron Lorentz factor $\gamma \approx 10^5$. This model applied to the Crab yields pulsations of much lower luminosity and frequency.

1. Introduction

The strong luminosity (between 400 and 900 nm) and the short period ($P = 0.5\,\mathrm{ms}$) of the reported optical pulsations from the young supernova remnant (SNR) SN 1987A (Kristian *et al.* 1989) raises problems for conventional models of pulsar optical emission. If relativistic beaming plays no dominant role, a rather small radiating area $\lesssim (cP)^2$ is implied, leading to an extraordinarily high optical brightness temperature ($kT_b >> 1\,\mathrm{GeV}$). It has not been demonstrated how such emission may arise close to a neutron star. On the other hand, it is widely accepted that pulsars may give rise to a wind of relativistic electrons and/or positrons ($e^{\pm}$) (Rees and Gunn 1974, Kundt and Krotscheck 1977, Kennel and Coroniti 1984, Cheng, Ho and Ruderman 1986). As suggested by Kundt and Krotscheck for the Crab nebula, ultra relativistic $e^{\pm}$ may give rise to *pulsed* emission *far from* the stellar surface where the relativistic wind runs into the pulsar dipole electromagnetic wave reflected from the inner boundary of the surrounding nebula. The main point of our paper is that such a mechanism can account successfully for the periodicity of the modulated optical signal reported from SN 1987A and it alleviates the optical luminosity problem posed by observations.

During the January 18 observation the brightness of the detected pulsed signal varied from magnitude 17 to 16 reaching at its maximum 1% of the luminosity of the SN 1987A remnant (Middleditch 1989). Thus, the maximum "optical" pulsed luminosity of the source was $L_{\mathrm{opt}} = 3 \cdot 10^{36}\mathrm{erg\ s^{-1}} \times \Delta\Omega/4\pi$, where $\Delta\Omega$ is the solid angle into which the pulsed radiation was beamed. At the same time the luminosity of the remnant (SNR) was $L_{\mathrm{SNR}} = 3 \cdot 10^{38}\mathrm{erg/s}$ (Burki and Cramer 1989). Subsequent observations failed to detect the pulses at a limiting magnitude lower by 2 than the maximum observed (Kristian *et al.* 1989) and by 8 than that of the SNR (Ogelman *et al.* 1989). By the end of April 1989 the remnant bolometric luminosity decreased to $L_{\mathrm{SNR}} = 1 \cdot 10^{38}\mathrm{erg/s}$. If L_P is the electromagnetic power of the pulsar and $\bar{L}_P$ is the time average (over several months) of this quantity, then the pulsed luminosity is $L_{\mathrm{opt}} = \eta L_P$, where η is the efficiency, while the SNR luminosity is $L_{\mathrm{SNR}} = f \cdot \bar{L}_P + L_0(t)$, where $0 < f \leq 1$ and the last term ($L_0 \geq 0$) represents the luminosity the remnant would have if the pulsar had no power. At maximum brightness of the optical pulses $\eta \geq 3 \cdot 10^{-2} f(\bar{L}_P/L_P)(\Delta\Omega/4\pi)$. The large value of the numerical coefficient constitutes the "optical luminosity problem."

Below, we find $\eta \lesssim 10^{-3}$. This implies that emission from the pulsar is beamed ($\Delta\Omega << 4\pi$), or the pulsar wind power is only sporadic ($\bar{L}_P << L_P$), or most ($L_P - fL_P$) of the pulsar spin-down power is either converted into kinetic energy of the nebula or reradiated at unobserved frequencies, (or all of the above). At any rate, we conclude that the pulsed-beam synchrotron emission model presented below can account for all observations if the relatively modest requirement $f(\bar{L}_P/L_P)(\Delta\Omega/4\pi) \lesssim 10^{-1}$ is met.

The cavity model is discussed in Section 3, while the constraints implied by the data on SN 1987A are considered in Sections 4 and 5.

2. Difficulties of magnetospheric models

Optical pulses from the Crab pulsar can originate in that neutron star's (outer) magnetosphere. But if the neutron star in SN 1987A is a weak-magnetic-field ($B_* < 10^9$ G) "millisecond" rotator (Kristian *et.al.* 1989, Pacini, Bandiera and Salvati 1989), it is hard to understand how the optical pulses could arise by an analogous process in its magnetosphere.

Because the Crab pulsar spin rate $2\pi/P_{\rm Crab} \approx 200\,{\rm s}^{-1} \approx 60$ times less than that of the 1987A neutron star, the emitting area (at the light cylinder radius) can be $\sim (60)^2$ times larger. In additon, the pulsed optical luminosity is an order of magnitude smaller in the Crab. The needed Crab optical brightness temperature is then $\sim 10^6$ eV, a value generally exceeded for synchrotron radiation of $e^{\pm}$ pairs created by γ-rays in the outer magnetosphere (Cheng, Ho and Ruderman 1986). Such emission mechanisms do not work for the pulsar in SN 1987A for two reasons.

i) A 10 GeV electron would give peak synchrotron radiation at photon energies above 100 MeV in the pulsar's *magnetospheric* field. The fraction of energy emitted into the optical band would then be very small, $\sim 10^{-5}$ of the total radiated synchrotron power.

ii) The detected neutrino burst confirmed that the neutron star in 1987A was formed hot, as expected (Hirata *et al.* 1987, Bionta *et al.* 1987). The present surface temperature of the star should be about $5\cdot 10^6$K. The whole magnetosphere between the surface of the star and the "light cylinder" (at $r_{lc} \equiv P/2\pi = 3\cdot 10^6$cm) should then be suffused with keV X-rays. In this (black body) X-ray flux, the mean free path for inverse Compton scattering by GeV electrons is $\sim 10^3$cm$<< r_{lc}$. Therefore effective potential drops along the field lines are limited to $\Delta U \sim 10^9$V by pair plasma created by the Comptonized photons: $e + X \rightarrow e + \gamma$ followed by $\gamma + X \rightarrow e^+ + e^-$. On the other hand, magnetospheric currents cannot give magnetic fields exceeding that of the neutron star. This limits the current flow density along open field lines to the Goldreich-Julian value $\vec{j}_{max} = (2\pi|\vec{B}|)^{-1}(\vec{\Omega} \cdot \vec{B})\vec{B}$ (Goldreich and Julian 1969), where $|\vec{\Omega}| = 2\pi/P$. The maximum power of those currents is $L_c = j_{max} R_*^3 \Omega^{-1} \Delta U$. Clearly $L_c > L_{\rm opt}$ is needed, as the electrons cannot radiate more energy than they carry. For $L_{\rm opt} = 3 \cdot 10^{36}$erg/s, a minimum potential drop along $\vec{B}$ of $\Delta U \geq 10^{14}$V is required. This last value is hugely in excess of the 10^9V value sustainable without electron pair avalanching. The magnetospheric accelerator would thus have been quenched long before it attains the required power.

It has also been suggested that the neutron star in SN 1987A is vibrating with the 0.5 ms period. Wang *et al.* 1989 proposed cyclotron radiation (in a $B_* \approx 10^{12}$G magnetic field) of ions powered by surface-penetrating shock waves as the mechanism for optical emission. However, it has not been shown how shocked ions could gain the necessary velocity perpendicular to $\vec{B}$ without being fragmented. Nor has it been shown how stellar vibration of reasonable amplitude could give rise to rapidly recurring shocks of requisite energy.

We conclude that an origin from within the stellar magnetosphere for the optical pulsations from SN 1987A has not been plausibly demonstrated for either the vibrational or the rotational model.

3. Pulsar cavities in supernova remnants

Far beyond the light cylinder of a pulsar in a vacuum, the spin-down power is carried largely in two forms (Rees and Gunn 1974, Kundt and Krotscheck 1977, Kennel and Coroniti 1984):

a) an ultrarelativistic $e^{\pm}$ wind,

b) electromagnetic (EM) fields of the magnetic dipole radiation (from the perpendicular component of the pulsar dipole) and a possible toroidal magnetic field (from the spin-aligned part of the dipole) carried with the wind.

Most of the wind energy is probably due to acceleration of $e^{\pm}$ by the very strong (time dependent) fields near the pulsar. For a rotating neutron star with a non-spin-aligned dipole moment the pulsar spin frequency would be impressed on the electron wind when the electrons are ejected (in a particular direction) from the outer magnetosphere and when they are subsequently accelerated. The resulting $e^{\pm}$ bunch structure would repeat at any (distant) point at the period P of the pulsar dipole radiation. If a similar electron injection and wind creation process were operative in a strongly pulsating neutron star a modulation at the vibration frequency of the magnetic dipole would also be expected.

When the pulsar is contained within a young SNR the large pressure from the pulsar wind and the radiation will create a "cavity" within the remnant. The pulsar cavity is terminated by a shock at radius d well within the outer nebula radius D. When pulsar emission is the main source of nebular power (Rees and Gunn 1974)

$$(d/D)^2 \sim \sigma \sim \left(\dot{d}/c\right),$$

where σ is the ratio of the pulsar outflow magnetic energy to the total energy density of the wind. For the Crab, Kennel and Coroniti obtain $\sigma \sim 3 \cdot 10^{-3}$ and $d_{\mathrm{Crab}} \sim 3 \cdot 10^{17}$cm, Kundt and Krotscheck find $\sigma \sim 1$ and $d_{\mathrm{Crab}} \sim 10^{18}$cm. Adopting similar values of σ for SN 1987A one would then infer a cavity radius $d \sim 10^{15}$cm in that SNR, smaller than that in the Crab by roughly the ratio of the SNR ages. We do not expect this estimate to be accurate for such a young remnant. However, our model only requires that a cavity with radius $d < D$ exist; for SN 1987A, $D \approx 10^{16}$cm at the epoch of interest (Papaliolios *et al.* 1989).

The outflowing ultrarelativistic bunches of $e^{\pm}$ do not radiate significantly in the nearly comoving EM waves. To the extent that EM energy is backscattered at the cavity wall, they will, however, pass through a magnetic field which may be taken to be comparable with that of the preshock incident magnetic field

$$B \sim B_{\mathrm{EM}} \approx \left(\sigma L_P/cd^2\right)^{1/2} \sim 2 \cdot 10^{-2} \left(L_{39}\sigma_{-2}d_{15}^{-2}\right)^{\frac{1}{2}},$$

This value of B_{EM} is similar to the one needed to understand the soft X-ray excess emission from SN 1987A, if one assumes equipartition in the nebula (Pacini 1989). If $\omega_B \equiv eB/mc > 2\pi/P$, the $e^{\pm}$ wind will lose energy in the cavity mostly by synchrotron radiation. Had $\omega_B < 2\pi/P$ the dominant loss mechanism would have been inverse Compton scattering.

4. Pulsed emission from the SN 1987A

In a $B \sim 10^{-2}$G cavity field, the characteristic synchrotron emission frequency is $\sim 10^{16}\gamma_6^2$ Hz, giving optical radiation if $\gamma_6 \equiv \gamma/10^6 \sim 1/6$. The fraction of beam energy converted to such radiation in a $d = 10^{15}$cm cavity is $\eta = \gamma\omega_B^2(e^2/mc^4)d \sim 10^{-4}$ for the same values. Because the optical radiation is emitted almost exactly radially, to a distant observer the radiation would appear to be coming from the pulsar itself. Thus, cavity and beam parameters of Section 3. could easily give the kind of optical luminosity observed from SN 1987A if the wind power were $\sim 10^{40} \times (\Delta\Omega/4\pi)$—about ten times the spin-down power of the Crab pulsar[1] if emission is isotropic.

Almost all of the beam power would ultimately be dissipated beyond the cavity boundary shock in the surrounding nebula where B is expected to be $\sim 10^2$ times larger than in the cavity. Refer to Section 1. for a discussion of how the current upper limit on the bolometric luminosity of the nebula can be satisfied.

We must now ask what constraints are imposed on the model parameters by insisting that the observed optical (or near infrared) synchrotron light is pulsed with the $e^{\pm}$ wind frequency 1/P. As shown in the next section, this approach yields for the various parameters values close to the ones adopted directly above. We find that the size of the nebula places an upper bound $\eta_{\max} \lesssim 10^{-3}$ on the efficiency of radiation allowed by the model.

A critical assumption is that the relativistic electrons synchrotron radiate in an *ordered* EM field of wavelength cP. This guarantees that the deflection from the radial direction of the radiating $e^{\pm}$ never exceeds an angle (θ_0, eq. [P10]) less

[1] The expected pulsed cavity emission from the Crab can be scaled from that from SN 1987A. For the "optical" frequency $\omega_{\rm Crab}/\omega_{1987} = [\gamma^2 B]_{\rm Crab}/[\gamma^2 B]_{1987} \sim [\gamma^2\sqrt{\sigma L_P}/d]_{\rm Crab}/[\gamma^2\sqrt{\sigma L_P}/d]_{1987}$. For comparable γ and σL_P, $\omega_{\rm Crab} \sim \omega_{1987}/500$ or λ(Crab) $\sim 10^2\mu$m. With similar approximations and assumptions the ratio of pulsed cavity emission luminosities from the Crab and SN 1987A is the ratio of the values of $\sigma L_P\gamma/d$, again correxponding to a reduction of about 500. Thus, the Crab's pulsed cavity far IR luminosity would be $\sim 10^{33}$erg/s. A bump of about this magnitude appears in the near ($\lambda \leq 3.5\mu$m) IR pulse shape of the Crab (Middleditch, Pennypacker and Burns 1983).

than the critical one beyond which the pulses would be washed out. If, instead, the field had been a collection of randomly oriented domains of size cP the average total deflection would have been too large, $\theta_0(d/cP)^{1/2}$.

5. Constraints on pulsed beamed synchrotron emission implied by the SN 1987A data.

By assumption, the optical signal is due to synchrotron radiation of relativistic $e^{\pm}$ (energy γmc^2) in transverse magnetic field of strength B alternating in direction with wavelength cP. Before entering an assumed emission zone of radial extent l, the electrons travel radially outwards a distance $d-l$ from the neutron star. The electrons radiate into a narrow forward cone of apex angle $\approx 1/\gamma$ about their instantaneous velocity direction, which is, itself, at an angle to the initial (radial) direction of flight. The latter angle is not greater than some maximum deflection angle θ_0 (eq. [P10]). Thus, the cross-sectional area of the emission region seen by an observer at infinity is $\approx \pi b^2$, where

$$b \approx d\theta, \qquad (P1)$$

and

$$\theta \approx \theta_0 + 1/\gamma << 1. \qquad (P2)$$

For the purposes of computation we take the optical brightness temperature to be $kT_b = 10^3\,\mathrm{GeV}\times\left(b^2/10^{12}\mathrm{cm}^2\right)^{-1}$ and the synchrotron frequency to be

$$\gamma^2 eB/mc = 2\,\mathrm{eV}/\hbar, \qquad (P3)$$

(i.e. $\gamma^2 B/10^8\mathrm{G} = 2$) to obtain (nearly) optimum efficiency of optical detection. The maximum extent of the nebula, $D \approx 10^{16}$cm places an upper bound on the size of the emitting region and its radial distance from the star: $l < D$, $d < D$.

Notation

γ—initial Lorentz factor of the radiating electron

θ—maximum angle between line of sight and initial direction of electron motion

θ_0—maximum deflection angle of electrons

d—radial distance from the neutron star to the emitting region

l—radial extent of the emitting region

πb^2—area of emission seen by observer

Δt—maximum allowed differential time of arrival (t.o.a.)

α, β, λ, $d_{16} \leq 1$—dimensionless parameters not greater than unity

Γ, $G > 1$—dimensionless parameters greater than unity

THE CONSTRAINTS

A class of constraints is introduced by the requirement that the optical pulses not be washed out. Let the upper bound on the differential spread in time of arrival of all photons in a pulse be $\Delta t = \alpha P/5 = \alpha \times 10^{-4}$s, i.e.,

$$c\Delta t = \alpha \times 10^{6.5}\text{cm}, \quad \alpha \leq 1, \tag{P4}$$

Any initial spread in energies ($mc^2\Delta\gamma$) of $e^{\pm}$ leads to a constraint $l \lesssim \gamma^3(c\Delta t)/\Delta\gamma$, less stringent than the following. We define

$$G \equiv \frac{1}{2}\left(\theta^2\gamma^2 + 1\right) \approx 1 + \frac{1}{2}\gamma^2\theta_0^2 + \gamma\theta_0. \tag{P5}$$

The differential t.o.a. constraint from time of flight delay of the emitting $e^{\pm}$ gives

$$l = \lambda G^{-1}\gamma^2(c\Delta t), \quad \lambda \leq 1, \tag{P6}$$

Differential t.o.a. because of different path lengths due to the transverse extent of the emitting region gives $b = \beta\theta^{-1}(c\Delta t)$, and hence

$$d = \beta\theta^{-2}(c\Delta t), \quad \beta \leq 1, \tag{P7}$$

(Strictly speaking $\lambda + \beta \leq 1$, but we are not concerned with factors of 2.) We note the following limits:

$$\theta_0 << 1/\gamma \Rightarrow G = 1,$$

$$\theta_0 \sim 1/\gamma \Rightarrow G \sim 2,$$

$$\theta_0 >> 1/\gamma \Rightarrow G = \frac{1}{2}\gamma^2\theta_0^2.$$

The inferred brightness temperature places a lower bound on the electron energy

$$\gamma = 10^{5.3}\Gamma\beta^{-2}\alpha^{-2}\theta^2, \quad \Gamma > 1. \tag{P8}$$

The efficiency of conversion of the electron energy to optical is $\eta \sim$(*Synchrotron power*)$\times(\gamma mc^2)^{-1} \times l/c$, i.e.,

$$\eta = \frac{\alpha\lambda}{G\gamma} \times 10^{3.9}, \qquad (P9)$$

where eq. (P3) was used to eliminate B.

Since the magnetic field traversed by the $e^{\pm}$ alternates in direction, the appropriate expression for the deflection angle is $\theta_0 \approx PeB/(2\pi\gamma mc)$, i.e.

$$\gamma^3\theta_0 \approx 10^{11.4}, \qquad (P10)$$

while the size of the nebula limits d and l,

$$l \leq d = d_{16} \times 10^{16}\text{cm}, \quad d_{16} < 1. \qquad (P11)$$

RESTRICTIONS ON γ

Consider the constraints (P6) to (P9) in the following two cases.

i)$\theta_0 \lesssim \gamma^{-1}$

From eq. (P10) this regime holds iff $\gamma^2 \gtrsim 10^{11.4}$, i.e. $\gamma \gtrsim 10^{5.7}$. However, the constraint (P6) with the subsidiary condition (P11) then gives a low efficiency, since $l = \alpha\lambda\gamma_6^2 \times 10^{18.5}$cm. Hence, $\alpha\lambda \lesssim 10^{-2}d_{16}$ and therefore $\eta \lesssim 10^{-4}d_{16}$.

ii)$\theta_0 >> \gamma^{-1}$

From point i) above, this can only hold if $\gamma < 10^{5.7}$. Now, from eqs. (P5) and (P10)

$$\theta \approx (2G)^{\frac{1}{2}}/\gamma \approx 10^{11.4}/\gamma^3.$$

Hence, using also eq. (P8), $\gamma = \Gamma^{\frac{1}{7}}(\alpha\beta)^{-\frac{2}{7}} \times 10^{4.0} < 10^{5.7}$, i.e.,

$$10^4 \leq \gamma < 10^{5.7}. \qquad (P12)$$

Now, from eqs. (P6), (P7) and (P9), respectively,

$$l \approx (\alpha\lambda)\gamma_4^6 \times 10^{8.0}\text{cm} \approx (\lambda/\beta)\Gamma^{\frac{6}{7}}(\alpha\beta)^{-5/7} \times 10^{8.0}\text{cm}, \qquad (P13)$$

$$d \approx (\alpha\beta)\gamma_4^6 \times 10^{7.7}\text{cm} \approx \Gamma^{\frac{6}{7}}(\alpha\beta)^{-\frac{5}{7}} \times 10^{7.7}\text{cm}, \qquad (P14)$$

$$\eta \approx (\alpha\lambda)\gamma_4^3 \times 10^{-6.4} \approx (\lambda/\beta)\Gamma^{3/7}(\alpha\beta)^{\frac{1}{7}} \times 10^{-6.4}. \qquad (P15)$$

Recall that α is the precision with which fine structure can be observed in the optical pulses in units of $P/5 = 0.1\,\mathrm{ms}$ and d_{16} is the maximum distance of the emitting region from the pulsar in units of 10^{16}cm. In principle, α is an observable number. The free parameters λ, β (and Γ) were introduced to replace upper (lower) bounds with equalities.

To satisfy $l \leq d$ we must have $\lambda \leq \beta/2 \leq 10^{-0.3}$. But (P13) and (P11) require $(\alpha\lambda)\gamma_4^6 < 10^{8.0} d_{16}$, giving, upon substitution in eq. (P15), $\eta < 10^{-2.4}(\alpha\lambda d_{16})^{1/2}$. We conclude that this model allows a maximum efficiency of

$$\eta_{\mathbf{max}} \approx 3 \cdot 10^{-3}(d_{16})^{1/2}, \tag{P16}$$

occurring for $\gamma = 10^{5.5}(d_{16})^{1/6}$ and the most favorable values possible of the free parameters ($\beta = 1$, $\lambda = 0.5$).

We thank Dr. John Middleditch for an informative conversation. This work was supported in part by NSF grants AST-86-02831 and NAGW-567 and 1618.

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